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Fully automatic CAD-design of the occlusal morphology of partial crowns compared to dental technicians´ design

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Abstract

Objectives:
The aim of this study was to compare the occlusal morphology of partial crown reconstructions made by dental technicians with reconstructions made by a fully automatic software process (biogeneric tooth model) in relation to the original natural tooth shape.
Material and Methods:
Stone replicas of natural teeth were measured three-dimensionally before preparing inlay and onlay cavities for ceramic restorations (n=5). For each preparation 5 reconstructions (in total n=25) were made by five dental technicians. Additionally, reconstructions were calculated automatically by a software based on the biogeneric tooth model (Cerec 3D). To compare the two different kinds of reconstruction an objective metrical similarity measure (shape similarity value, SSV) based on calculated volumes between compared datasets was used.
Results:
In 22 of 25 cases the reconstructions made by the CAD software was more similar to the original situation than the reconstructions made by the technicians. Mean average SSV of reconstructions made by the technicians (310.2 +/- 78.8 µm) was significantly higher ($p<0.05$) than mean SSV of CAD reconstructions (biogeneric model) (222.0 +/- 47.7 µm).
Conclusions:
Concerning the design of naturally shaped occlusal inlay/onlay surfaces, a fully automatic CAD system can be at least as good as conventional wax-ups by dental technicians.
Clinical Relevance:
The adjustment of a dental restoration, regarding the morphology of the surrounding tooth structures, is still an ambitious challenge for the dentist.

Keywords:

Similarity measure, CAD/CAM, Biogeneric tooth model, Occlusal morphology;

Introduction

A fundamental consideration of restorative dentistry is the design of occlusal surfaces [1]. This is not only the key for mastication, but also for the stability of the entire stomatognathic system. Designed occlusal surfaces should correspond to a natural shape with functional fissures and cusps, adapted to the anatomical shape of the adjacent teeth and antagonists. Concepts of occlusal design reflect present biomechanical ideas, concerning the functioning of an occlusal surface [1–3].

At the moment, there is a gradual change in restorative dentistry from manual towards computerized fabrication, by means of computer aided design (CAD) and computer aided manufacturing (CAM) devices [4–6]. However, especially the design of functional occlusal surfaces, still often needs considerable interaction and the experience of a human operator [7–8]. More advanced CAD software systems try to reduce demanding and time-consuming interactions between the dentist and the CAD/CAM device. Hereby algorithms to fit the occlusion to static or dynamic bite registration are used[9–11].

But still there is a desire for a CAD system, which generates occlusal surfaces fully automatic. Therefore, a mathematical representation of tooth surfaces and their natural variations called "biogeneric tooth model" was introduced [12, 13]. Based on a 3D-data library of hundreds of scans of intact unrestored posterior human teeth, this model is capable of deducing an entire occlusal surface from the residual substance of a partially destroyed tooth [13, 14]. The biogeneric tooth model is already implemented in current CAD software (Cerec 3D, Sirona, Bensheim) and promises to make fully automated design of partial crowns possible [15]. Compared to conventional CAD software, this mathematical model already proofed its efficiency in generating CAD/CAM-partial crowns with natural tooth morphology [16]. However, the question remains, if this software can compete with well-trained dental technicians concerning the design of natural occlusal surfaces.

The aim of this study was to compare the occlusal morphology of reconstructions made by dental technicians with reconstructions made by the biogeneric tooth model. The different reconstructions were set in relation to the natural tooth shape before simulating an inlay/onlay preparation. Morphological comparisons were performed with the aid of a 3D-similarity measure.

Material and Methods

Original occlusal surface

For this study five subjects were randomly selected from a pool of young adults with completely intact tooth surfaces, no tooth restorations and no caries. All subjects agreed to participate in the study by informed consent. The average age was 25 years (range from 21 to 33 years). Polyether impressions (Impregum, 3M Espe, Seefeld, Germany) of both jaws were made and subsequently stone replicas (Fuji Superstone, white; GC Corp, Tokyo, Japan) were fabricated. The occlusal surfaces of the molars were measured with a 3 D scanning device (Scan 3D Pro, Willitec, Munich, Germany) [17]. The resolution of the measuring process was 30 × 30 µm (x,y), yielding approximately 100,000 surface points per tooth. The accuracy in height direction (z) was approximately 10 µm.

Designing the reconstruction

$$\text{shape similarity value} = \frac{Vol_{pos} + abs(Vol_{neg})}{A_{tooth}}$$

Preparations for adhesive inlays/onlays were simulated on the stone replicas (Fig. 1). For this, one molar tooth was randomly chosen in each subject. Concerning the preparation, at least one cusp was left untreated. The casts of the upper and lower jaw were saw cut and fixed in an articulator (SAM Präzisionstechnik GmbH, Munich, Germany). Bite registrations of the antagonists were taken with a scanable registration material on vinyl polysiloxane basis (Metal-Bite, R-dental, Hamburg, Germany). The treated teeth and the antagonist registrant were scanned with an opto-electronic intraoral camera (CEREC-3D, Sirona, Bensheim, Germany). Using Cerec 3D CAD software v3.00, based on the biogeneric tooth model [13, 18], models were trimmed virtually and preparation margins were set. Reconstructions were performed fully automatic in the inlay/partial crown modus with no interaction through the operator. Reconstruction data were saved and converted into STL-format and xv-format files (DentalVisual, software developed by A. Mehl). Additionally, five well-trained dental technicians (all of them at least for seven years in business) were instructed to wax up the original tooth form in the resulting inlay/onlay cavities as well as they could. The technicians had no time limit. They were instructed to reconstruct occlusal surfaces, which should correspond to a natural morphology, adapted to the shape of the adjacent teeth and antagonists. No especial guidelines or wax-up concepts were recommended. Each wax-up model was scanned with the above-mentioned 3 D scanning device (Scan 3D Pro).

3D similarity measure

After the original tooth surfaces were reduced to the extent of the corresponding inlay/onlay preparation, all reconstructions (computer-based reconstructions and conventional reconstructions made by the technicians) were superimposed with their original surface according to a best-fit method by the program Match3D 2.5 [19]. Difference images, displaying colour-marked local 3D-distances (Fig. 3 and 4) were calculated between the datasets by evaluating distances point by point in z-direction (perpendicular to the occlusal surface, about 100.000 surface points (k)) [19]. The "shape similarity"-value (SSV) was defined as the sum of the positive volumetric deviation and the absolute negative volumetric deviation, divided by the surface area of the difference image:

In mathematical theory, this value corresponds to a l_1-distance metric in k-dimensional vector space by $\left\| \vec{v}_{tooth1} - \vec{v}_{tooth2} \right\|_{l_1} / k$. Superimposed surfaces, which are more dissimilar, come along with higher volumetric deviations resulting in a high SSV and vice versa. With this measure a) similarities between computer-based reconstructions and corresponding natural tooth forms (n=5, group A, subgroup 1) and b) similarities between reconstructions made by the technicians and corresponding natural tooth forms (n=25, group B or n=5 for each technician, subgroups 2-6) were calculated.

Statistical analysis

Statistical analysis was performed with SPSS 14.0 unless otherwise stated. All significant differences were detected at a 95% confidence level. The following null hypothesis was to be tested by student t-test: there is no statistically significant difference concerning the shape similarity measure (SSV) between sample group A (computer-based reconstructions matched to natural teeth) and sample group B (dental technician-based reconstructions matched to natural teeth). Before starting the experiments, power analysis was done with G*Power Version 3.1.0 computer program [20]. Data about relevant difference between the two sample groups A and B and about estimated standard deviations were drawn from a preliminary study [21]. Setting the α-level at 5%, five samples in group A and twenty-five samples in group B were needed to have at least an 80% statistical power. Subgroup SSV means of CAD reconstructed surfaces (subgroup 1) and surfaces reconstructed by each single technician (subgroups 2-6) were analysed by one-way ANOVA with post hoc LSD-test.

Results

At first view, it is obvious that reconstructions based on the same original surface considerably differ from each other (Fig. 2). Fig 3 and 4 show the difference images for two cases.

The mean shape similarity value (SSV) of reconstructions made by the technicians was 310.2 (+/- 78.8) µm. The mean shape similarity value (SSV) of the CAD reconstructions (biogeneric model) was 222.0 (+/-47.7) µm (Fig. 5). Only in three of twenty-five samples the reconstruction made by the technicians showed a lower value of the SSV than the reconstruction made by the CAD software (Fig.6). In case 2, technician number 3 and in case 5, technician numbers 2 and 4 were able to design more natural tooth morphology according to the similarity measure SSV. Calculated values of the volume between two compared surfaces are shown in the graph (Fig. 6).

Based on the 95% confidence level the null hypothesis was rejected. Hence, based on the similarity measure SSV, computer-based reconstructions were considered to be significantly more similar to the original occlusal surface than the reconstructions made by the technicians ($p<0.05$). Mean SSV difference was 88.16 and 95% confidence interval of the difference was [12.72; 163.60]. Comparing the different single group means of SSV, a higher diversity was shown. CAD reconstructions were significantly more similar to the original morphology than conventional reconstructions made by dental technician 1 and 3. However, technician number 2, 4 and 5 showed no significant difference compared to the CAD group.

Discussion

Length measurement and descriptive characterization are the only references for comparing the morphology of occlusal surfaces [22-26]. However, linear metrical parameters are not suitable for the comparison of complex 3-dimensional structures like teeth. Other literature dealing with occlusal morphology or wax-up techniques are solely descriptions of occlusal surface features with different weighting of these features [27-29]. A visual comparison of manufactured tooth surfaces is therefore highly dependent upon our experience and imagination, thus leading to irreproducible evaluations. Hence, an objective measure that is able to display similarities/dissimilarities of different occlusal surfaces was required for this study. By means of the shape similarity value (SSV), no reference points have to be set. This way of comparing tooth forms is technically robust and allows standardized and reproducible morphological comparisons. Contrary to calculating the standard deviation [14], the SSV includes the deviations in a linear way and therefore does not overestimate outliers with quadratic terms. This reduces errors, which may arise from differences on steep inclines or measurement errors made by optical scanners. A limitation of the measure is the problem that only an average value is calculated. This measure does not metrically indicate which areas of two surfaces are coincident or different.

The final results of this study, based on the used similarity measure SSV, approved our alternative hypothesis. In case of an inlay/onlay situation the fully automatic biogeneric tooth model is able to reconstruct missing areas of the occlusal morphology more naturally than well-trained dental technicians. This means that one of the key points in oral rehabilitation, the adaptation of a dental restoration to the surrounding tooth structures, can be achieved by a fully automatic dental CAD program. Higher SSV variances of the occlusal surfaces waxed up by the dental technicians reflect the individuality of wax-up patterns. Nevertheless, in some single cases, it is certainly possible that a conventional reconstruction can produce a more natural tooth form.

The tested biogeneric CAD program is obviously able to provide fully automatic design for the manufacturing of partial crowns with a natural occlusal morphology. This confirms a recent study of Ender et al. 2011, which assessed the naturalness of fully automated occlusal design by subjective visual ratings of dental experts. These ratings are based on a detailed questionnaire, asking for certain features of tooth morphology like fissures and cusps. In contrast, by means of an objective similarity measure, this study compares each reconstruction with the original tooth surface in pair wise comparisons. Additionally, complete groups of CAD reconstructions and conventional reconstructions were compared as well. As a result, this study contributes objective and reproducible metric data to the debate about effectiveness of fully automated occlusal design. However, direct information on the esthetical fit of the reconstructed crowns as demanded by experts [16, 30] is not provided. A further limitation of this study is that proximal, buccal and oral surfaces were not taken into consideration. Beside this, a point of critique could be that functional aspects are not explicitly assessed.

A recent study of Ellerbrock and Kordaß also analysed whether computer generated occlusal surfaces are equivalent with those waxed up by experienced dental technicians [31]. Similar methods (similarity measure) for comparing occlusal surfaces were utilized. It is concluded that comparable occlusal surfaces can be achieved by computer-aided design. Nevertheless, that study is simply based on casuistics and descriptive statistics. Another difference between our studies was that the generated occlusal surfaces were not referenced to the original surface.

In conclusion, it could be demonstrated that, within the limitations of the study, a fully automatic CAD system can be at least as good as conventional wax-ups made by dental technicians with regard to the design of naturally shaped occlusal inlay/onlay surfaces. In future, the automatically design of complete single and multiple tooth restorations could become possible. Algorithms that can derive the morphology of a tooth from the shape of neighbour and antagonistic teeth, are necessary. Numerous benefits associated with CAD/CAM generated dental restorations, like cost-effective production, increase in quality and reproducibility [5, 6], may also be transferred to even larger reconstructions.

Conflict of interest

The authors declare that they have no conflict of interest.

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Figure Legends

Fig. 1
Scan of an original (left) and preparated (right) tooth surface

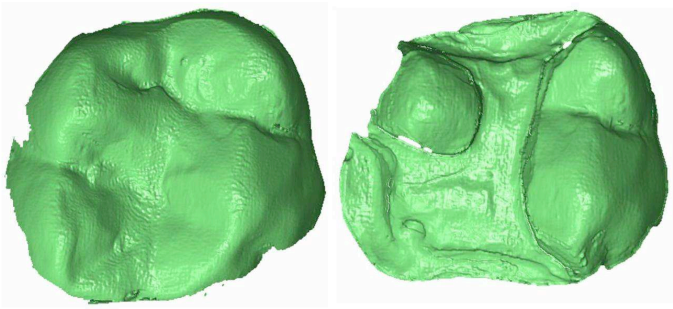

Fig. 2
Case 4 – **a)** Scan of original tooth surface **b)** virtual CAD reconstruction and **c-g)** scans of wax-up models by dental technicians

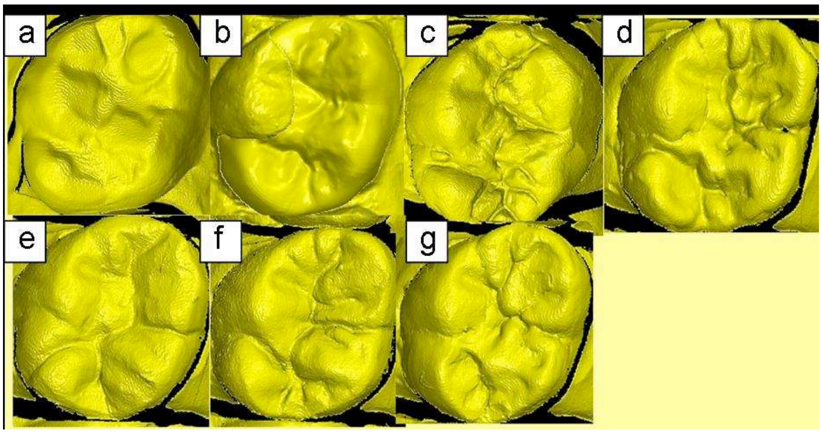

Fig. 3

Case 4 – Difference images displaying colour-marked local 3D-distances **a)** between original surface and virtual CAD reconstruction and **b-f)** original surface and wax-up by dental technicians; green = low differences, red or blue = high differences

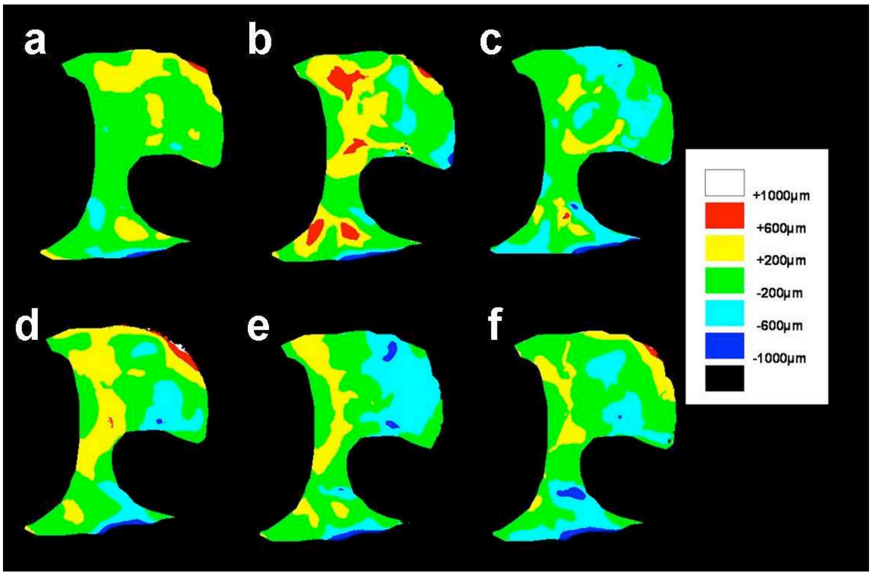

Fig. 4

Case 2 – Difference images displaying colour-marked local 3D-distances **a)** between original surface and virtual CAD reconstruction and **b-f)** original surface and wax-up by dental technicians; green = low differences, red or blue = high differences

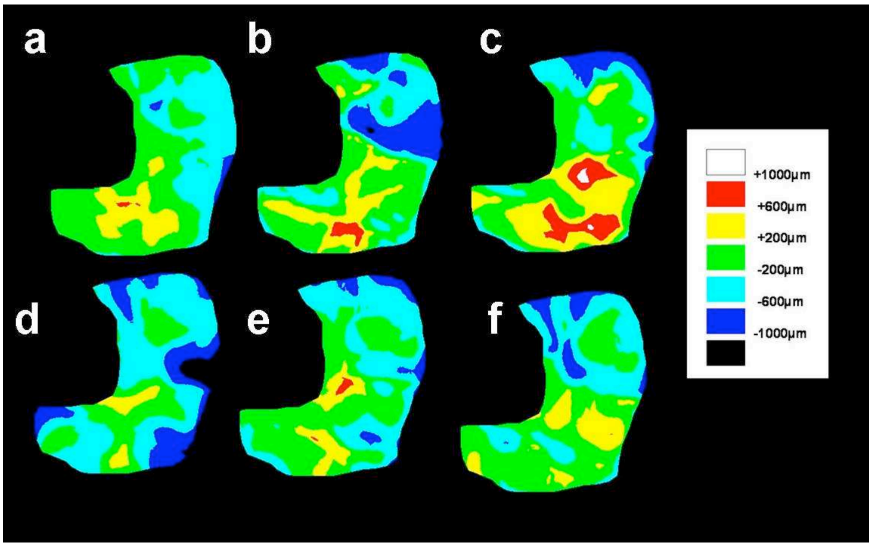

Fig. 5

Error bars displaying mean shape similarity value (SSV) [µm] and standard deviation of comparisons **a)** between original surfaces and corresponding virtual CAD reconstructions and **b)** between original surfaces and wax-up models by dental technicians.

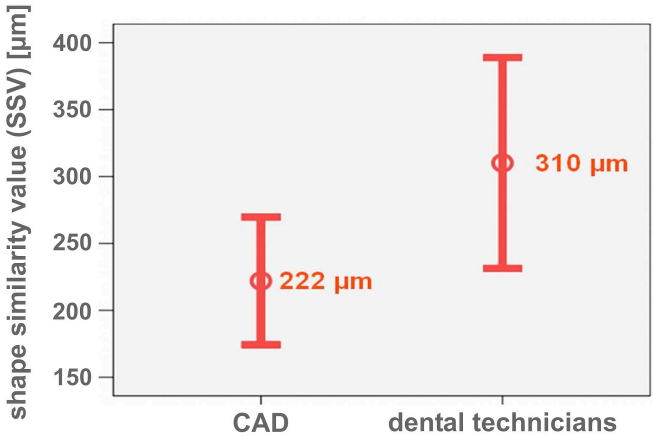

Fig. 6

Cases 1 to 5 – Volumetric deviations in comparisons of original surfaces with corresponding virtual CAD reconstructions (biogeneric model, BIO) and wax-up models by dental technicians 1 to 5 (T1-5).